Orion Inspection Planning - Lessons Learned Rev 4

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2014 In-space Inspection Workshop

Inspection of Orion at ISS

- **Orion-inspection research by ISAG took place from 2008 through 2011*.**
  - Work relevant to ISS Visiting Vehicle inspection continues.
  - Work relevant to Orion inspection for non-ISS missions continues.

- **Original assumptions (2008-2011), involving hardware**
  - Vehicle would be docked at Node 2 Forward, or Node 2 Zenith for 210 days
  - Inspection would occur 7 days before undocking
  - Inspection, based on Space Shuttle heritage, would consist of
    - Full-surface, primarily robotic, imagery "survey" to detect damage suspects. Includes coverage verification.
    - Followed by, if needed, focused inspection to determine nature and criticality of any damage detected
- **Thermal Protection System (TPS) Inspection planning research (2008-2011)**
  - Driven by estimated risk of Loss of Crew and Loss of Mission associated with critical TPS damage.
    - Critical TPS damage leading to catastrophic spacecraft reentry represented one of the largest estimated risks for Orion missions.
  - Guided by TPS failure criteria (next slide).
  - Imaging and associated robotic resources already on the ISS evaluated.
  - Imaging resources already space qualified (e.g. for the Space Shuttle) evaluated (e.g. Laser Camera System [LCS], Laser Dynamic Range Imager [LDRI]).
  - Imaging and sensing resources at various technology readiness levels (TRLs) reviewed.
  - TPS addressed by ISAG effort mainly consisted of the tiles on the Back Shell and Forward Bay Cover (FBC) of the Crew Module (CM).

*In 2010, the Constellation Program, which planned frequent Orion "Crew Exploration Vehicle" access to the ISS, was canceled. The Orion spacecraft development was continued, but principally directed at non-LEO exploration.

Inspection Assumptions and Strategy

- **Thermal Protection System (TPS) Failure Criteria (to be addressed by inspection)**
  - Allowable depth of tile penetration (specific values, depending on location)
    - Tile damage main cavity, generally observable by line-of-sight imager (sometimes with difficulty).
    - Deeper damage cavity protrusions, called "fingers", more difficult to view, but often not a concern, depending on geometry.
  - Allowable area (specific value, relevant during the study) of Strain Isolation Pad (SIP) penetration. The SIP is immediately under the tile.
    - SIP penetration area somewhat observable by a line-of-sight imager.
  - Allowable degree of core buckling (currently zero core buckling allowed).
    - Not directly observable, in general, by a line-of-sight imager.
    - Appeared, from X-ray/CT imagery, to be reasonably correlated with SIP penetration area exceedance.
- **Derived Survey Inspection Criteria**
  - Must detect 0.25"-diameter entry hole. Entry holes smaller than that were not believed to be associated with any of the TPS failure criteria.
    - Based on testing and modeling.
  - A 0.25"-diameter entry hole was estimated to be over 50% likely, on the average, for a 210-day ISS-docked mission.

Summary of Lessons Learned and Recommendations

- **Survey Inspection**
  - High probability (>99%) of detection of critical damage likely with existing robotic ISS assets.
    - Full robotic-based surface coverage is anticipated.
    - High probability detection may require redundant, independent screening.
  - White painted tile superior to black tile for MMOD damage detection
  - Line-of-sight illumination preferable
    - Causes core material to “glow” through entry hole

Summary of Lessons Learned and Recommendations (continued)

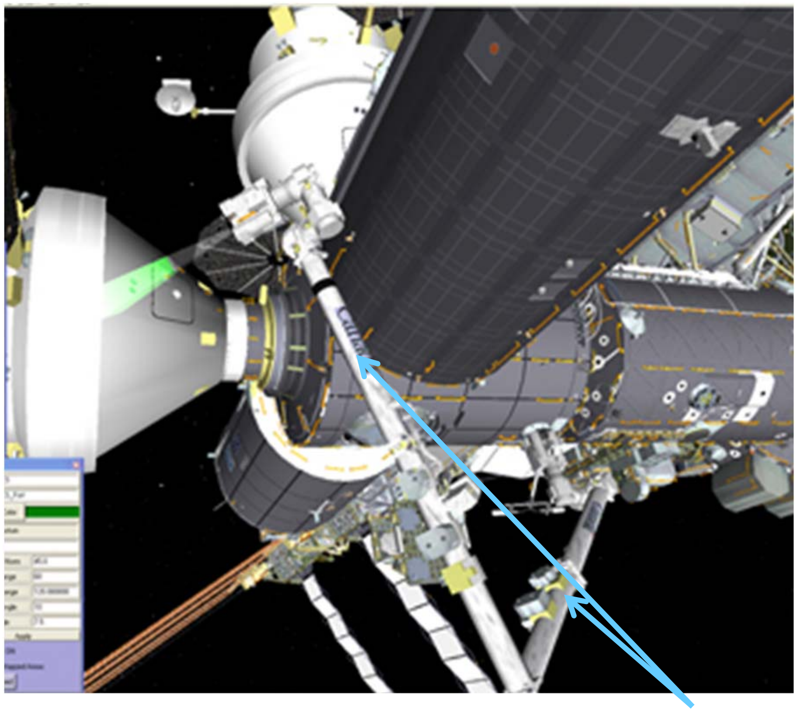
- **Focused Inspection**
  - Marginal focused inspection capability with existing robotic ISS assets
    - Poor depth measurement resolution could lead to unnecessary scrapping of vehicle (a “loss-of-mission” outcome) for a damage cavity that might otherwise be cleared for safe reentry with better sensory data.
  - Inherent 3D sensor recommended
    - Superior to stereo from 2D when an internal surface is featureless, and when the entry hole is too small for good parallax)
  - High-resolution, color robotic imaging capability recommended
    - The OTVC camera (later slides), which exists on-board and is capable of close viewing, is grey scale.
  - UV illuminator recommended
    - At least one sub-surface material is fluorescent.
  - Penetrating sensor recommended (e.g. back-scatter Xray), when compact, robotically deployable, space qualified technology is ready.
    - Damage geometry may involve voids that cannot be seen line-of-sight through the entry hole.
    - Even if damage geometry can technically be characterized through the entry hole, there may be a large number of viewing positions required, and the merging of data from those views into a single 3D model may be a challenge.

Step 1: Survey Inspection

What is the probability of detecting critical damage on Orion TPS, using sensors under consideration?

Can the sensors be placed in needed viewing positions?

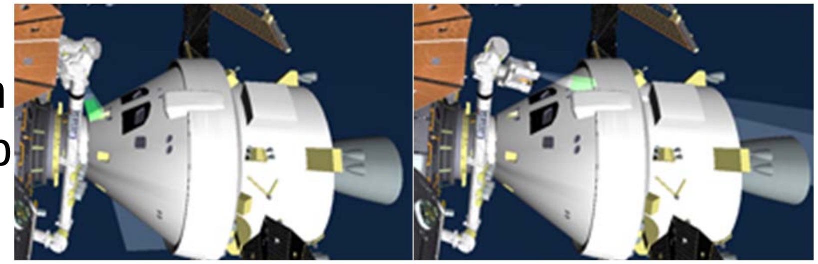
Survey Inspection of the MPCV at Node 2 Forward



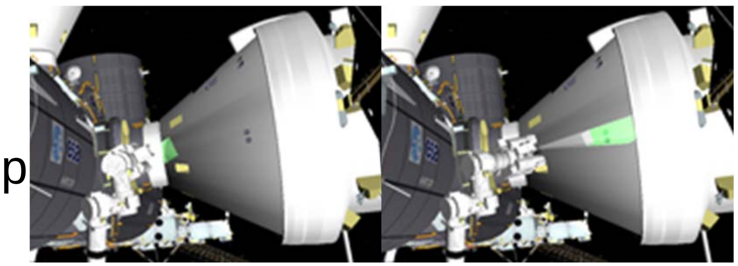
Space Station Remote Manipulator System (SSRMS) arm, based at the Node 2 Power/Data Grapple Fixture (PDGF) with Latching End Effector (LEE)-based MSS Camera inspecting the Crew Module

Here, the SSRMS end-effector camera, a Mobile Servicing System (MSS) type, is being used for the survey inspection.

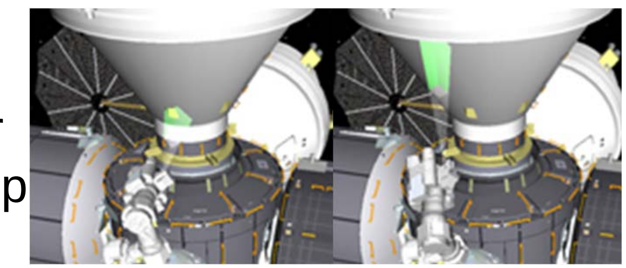
Zenith sweep



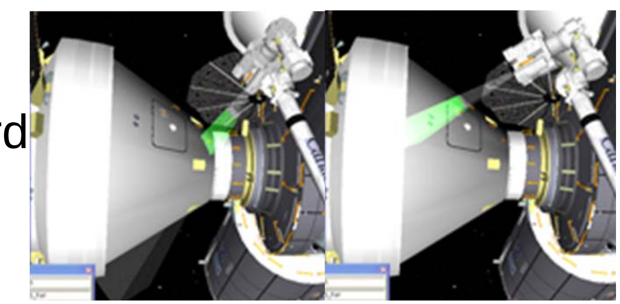
Port sweep



Nadir sweep



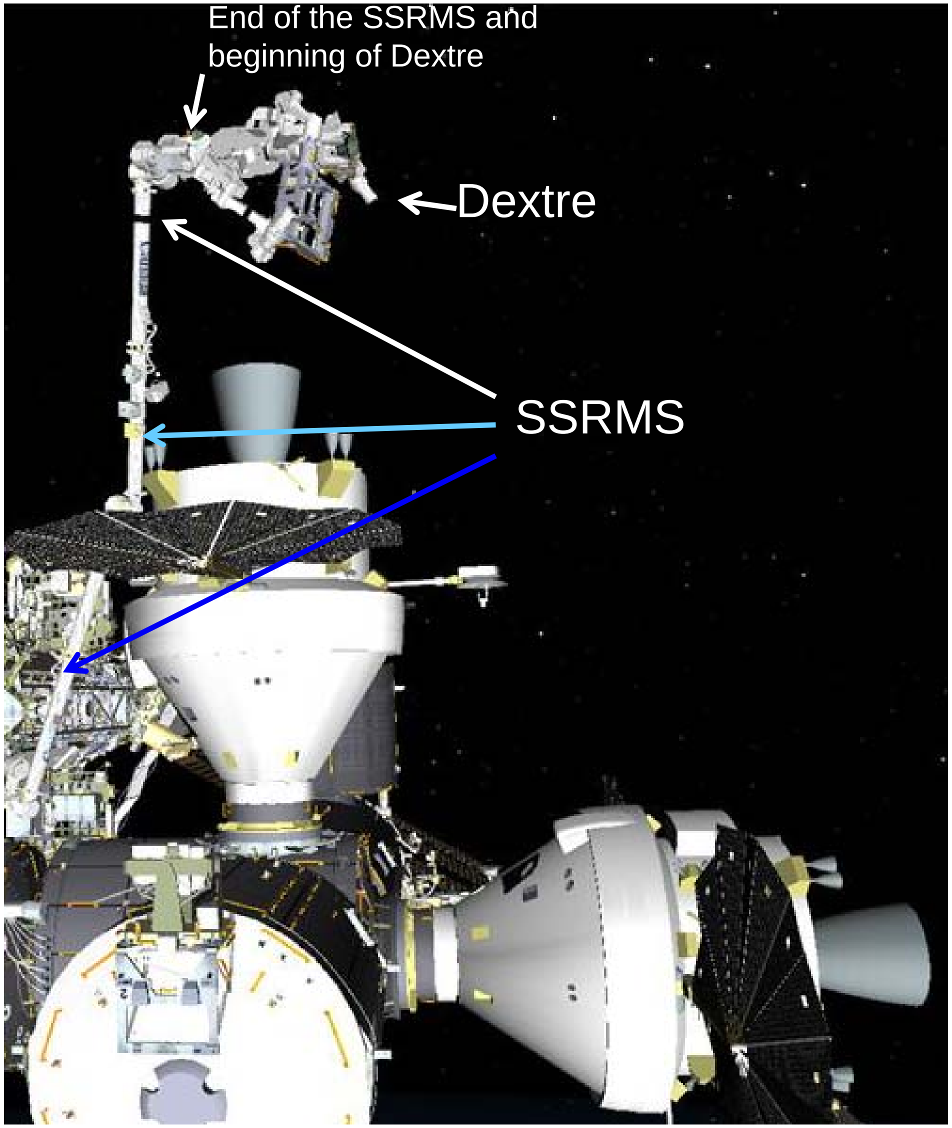
Starboard sweep



Inspection of the MPCV at Node 2 Zenith

Here, the SSRMS has grappled Dextre, an ISS external robot which also has several MSS-type cameras.

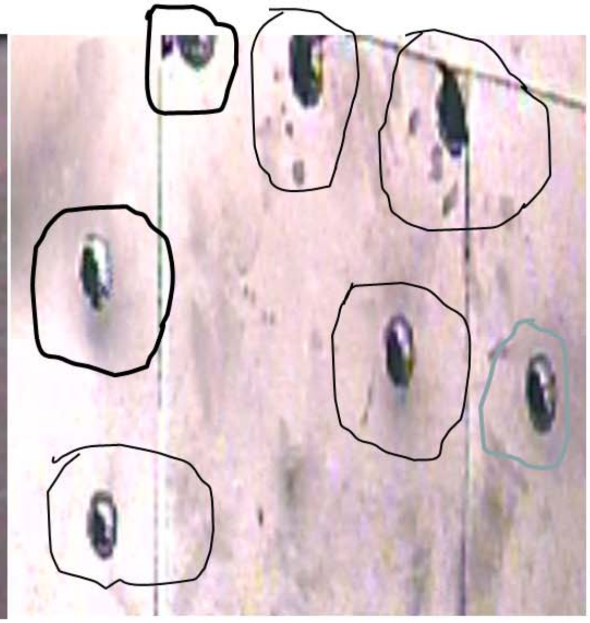
The illuminators built near the MSS camera lines of sight have been more dependable on Dextre than on the SSRMS end effector.



With the SSRMS based on the Mobile Base System (MBS) platform, there is ample margin in reach for a TPS survey by the SSRMS cameras alone. Here, Dextre is also shown, attached to the end of the SSRMS.

Sample MSS Camera Imagery under Mock Solar Illumination, with Screener Annotations

SB01



SW14

SB08

Example screener-annotated slide from a damage detection blind study in the Fall of 2010. The MSS images were captured under conditions equivalent to 10' range at full zoom (7.7 mm focal length) and simulated sunlight or MSS artificial illumination. The images were all subject to the degradation associated with the mockup ISS Video Baseband Signal Processor (VBSP)* which discarded an entire field of information (and therefore half of the vertical resolution). In 2013, the VBSP was replaced with newer technology with improved downlinked image quality.

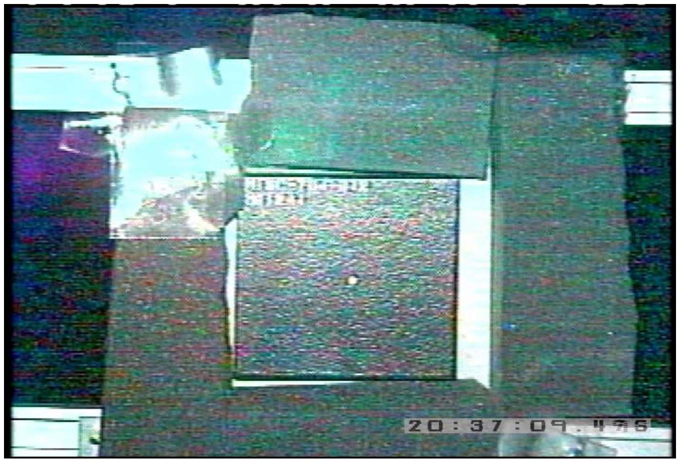
MSS Camera PoD Blind Testing Results

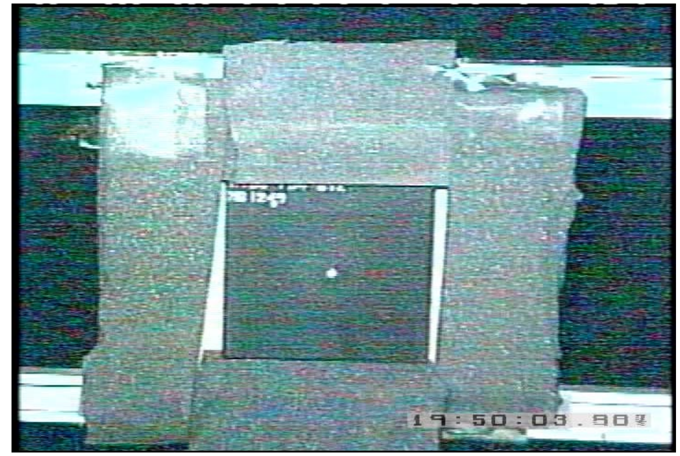
Test Cases (below) \Inputs and Estimated Probability of Detection (PoD) - (Across)	Number of trials (given)	Number of successes (given)	Confidence Level (given)	Minimum PoD for 1 Screener (POD_1): Estimated Minimum Single-screener PoD - (calculated)	Minimum POD for 2 Independent Screeners or Teams POD_2 = (1 - PF2), where PF2 = PF1 * PF1 (i.e. probability of both teams failing) and	Minimum POD for 3 Independent Screeners or Teams POD_3 = (1 - PF3), where PF3 = PF1 * PF1 * PF1 (i.e. probability of all 3 teams failing) and PF1 = 1 - POD_1
MSS Imagery Blind Testing, All Screeners, Off-axis Illumination (Black Tiles Only, 0.24" ≤ Entry Hole ≤ 0.27")	84	83	0.95	**0.93**	0.995	0.9996
MSS Imagery Blind Testing, All Screeners, Distributed Illumination (Black Tiles Only, Including transplanted black regions of white tiles, 0.24" ≤ Entry Hole ≤ 0.28")	21	21	0.95	**0.80**	0.962	0.9925
MSS Imagery Blind Testing, All Screeners, On-axis Illumination (Black Tiles Only, 0.24" ≤ Entry Hole Size ≤ 0.27")	36	36	0.95	**0.90**	0.989	0.9989
MSS Imagery Blind Testing, All Screeners, All Illumination (White Tiles Only, 0.22" ≤ Entry Hole Size ≤ 0.28")	108	106	0.95	**0.93**	0.996	0.9997

MSS camera based probability of detection (PoD) estimates (right three columns) based on screener testing in the Fall of 2010.

Survey Illumination Examples and Issues

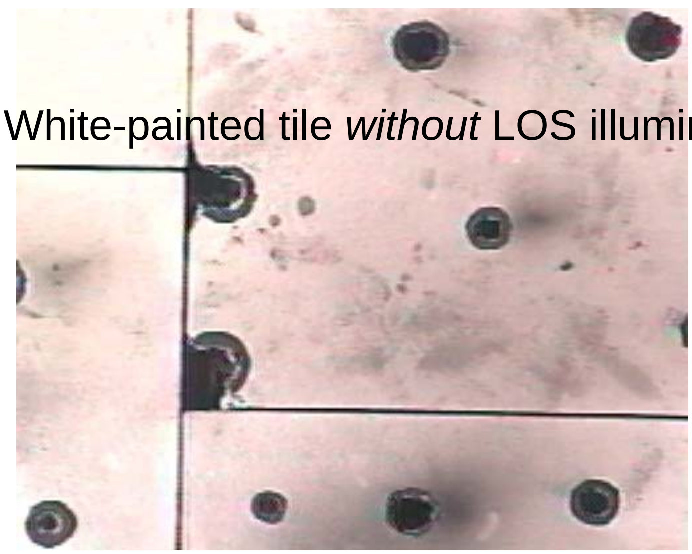
SSRMS and Dextre MSS-type Imager with Relevant* Line-of-sight (LOS) Illumination





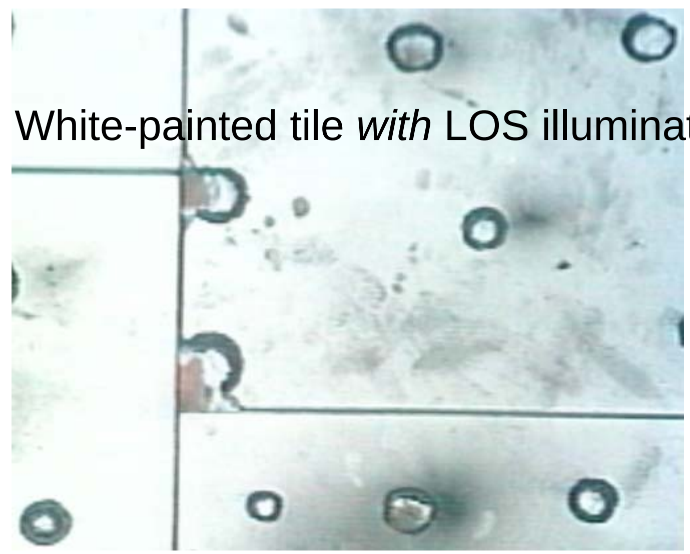
Internal silica glows against entry hole rim, for both black and white (painted) tiles, given line-of-sight illumination. This gives evidence that **an actual entry hole is present**, and the suspect feature is not missed or considered just a blemish.

White-painted tile *without* LOS illumination



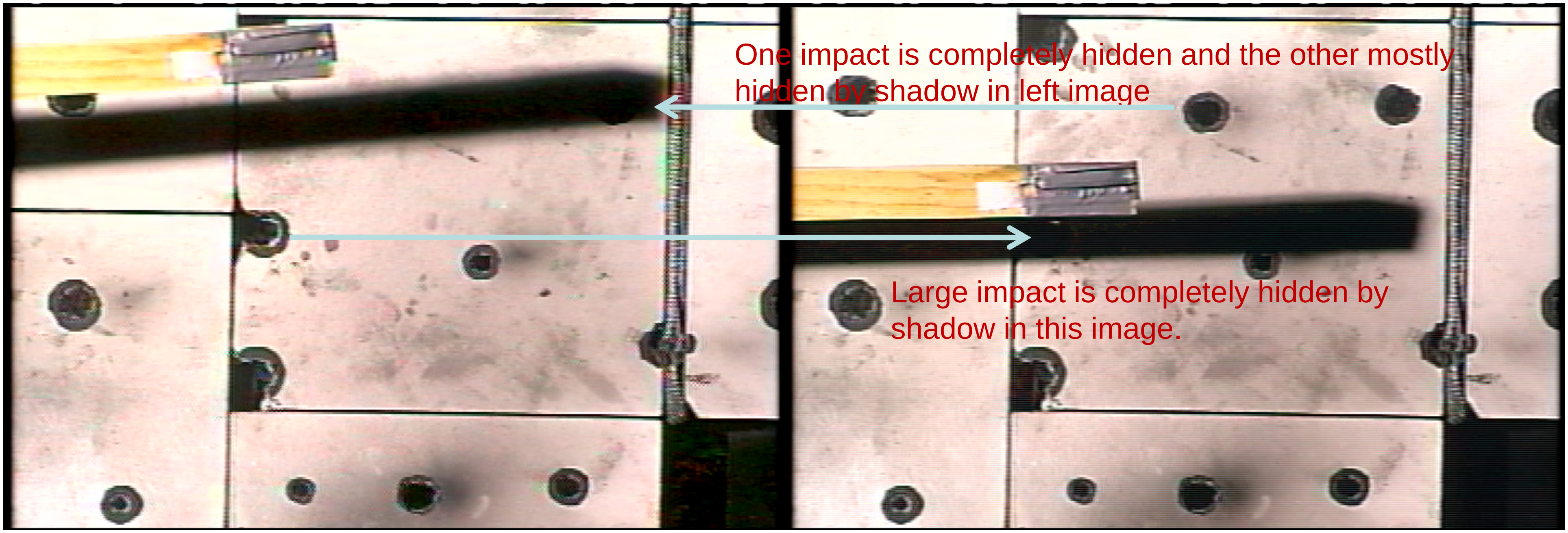
In 2010, white-painted tiles were considered the most likely after the first Orion mission.

White-painted tile *with* LOS illumination



*Flight-similar illuminators were set up for this camera testing.

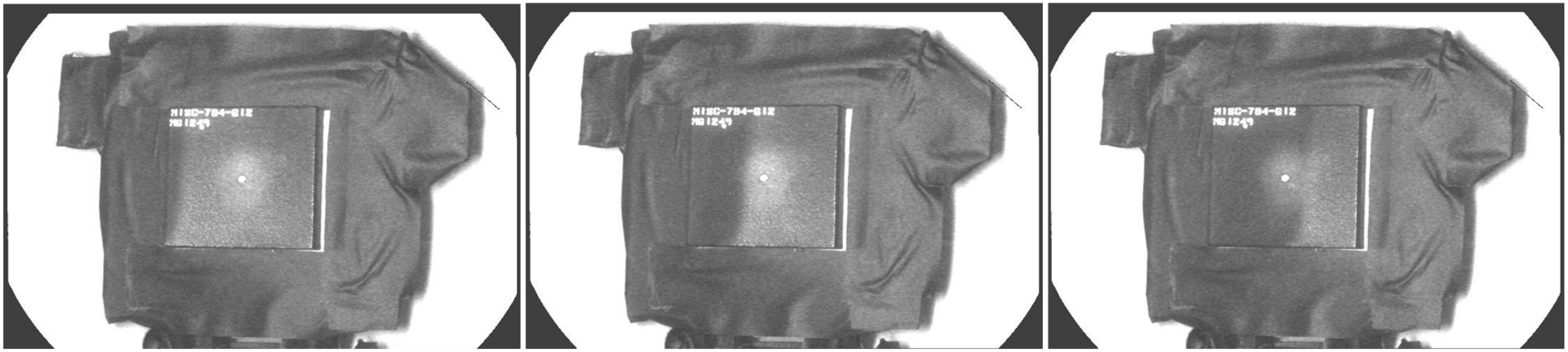
Problem: For MSS-type imagers, operating in daylight, passing shadows can completely obscure damage



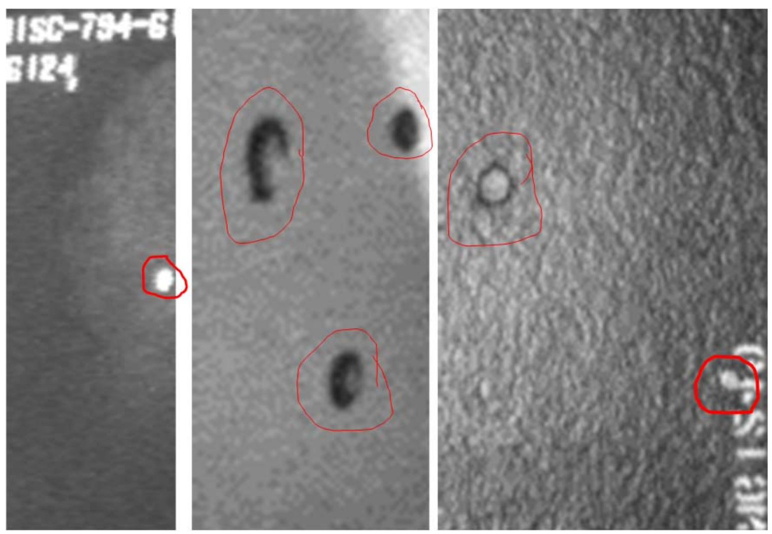
Day with high-contrast "sun" shadow another entry hole and nearly covering a third (see left image for reference).

Day with high-contrast "sun" shadow covering an entry hole (see right image for reference).

Sample LDRI Imagery



Sequences of "Level-1" LDRI Images for which a simulation of hardware shadowing the "sun" is demonstrated. Note that both tile impact features (the impact in the center and the impact adjacent to the serial numbers) remain clearly visible and detectable regardless of the progress of the shadow.



Example Hypervelocity-impact Entry Holes and Annotations by Screeners in Blind/Subjective Detection Testing. Note a small entry hole (diameter 0.19") in the upper-left by the serial numbers that was not circled. The larger entry hole in that image (the one that was circled) has a diameter of 0.27". The left and right images are of black tile cases and the center image shows a white tile. All three images have an impact with a diameter on the order of 0.25".

Step 2: Focused Inspection (FI)

Can FI sensors under consideration be used to help determine the criticality of damage?

Will the results be of adequate resolution, to avoid unnecessary loss-of-mission decisions?

Basic Focused Inspection Imagery Approaches

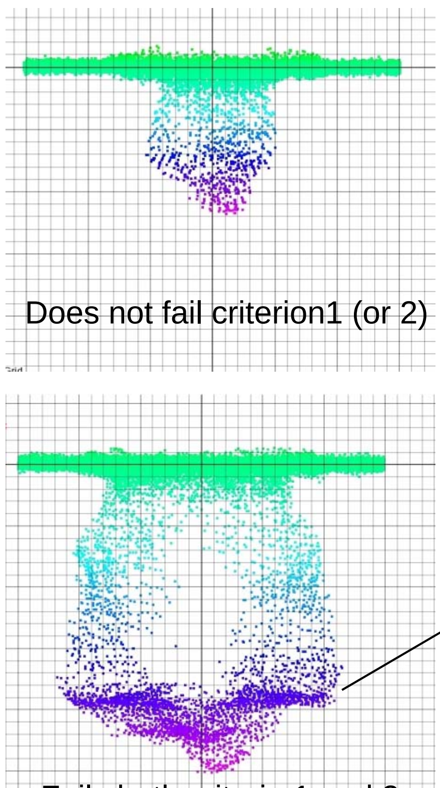
- **Deploy sensor robotically* for close, high-resolution viewing of a tile damage cavity of concern.**
  - *Crew space walks could also be considered, but are risky and time consuming.
- **Produce 3D characterization of the damage cavity**
  - Use an inherently 3D sensor (e.g. LCS)
  - Use a 2D imager (e.g. the OTVC**) from 2 or more viewpoints
    - SSRMS grapples the external robot called Dextre, whose “arms” have OTVCs at their end points.
    - An OTVC has two illuminators, is grayscale, and fixed focus, with an optimal focus distance of about 16”
    - The large number of robotic joints leading up to an OTVC allows many degrees of freedom for positioning and orientation.
    - Each OTVC center is 2.5” from a roll axis, and the roll angle can be known very precisely. Thus the eyepoint position movement due to such a roll can also be known very precisely, assuming the SSRMS and Dextre don’t otherwise move during such a roll. Thus, an OTVC can be considered as a source of stereo or multiview imagery collection.
  - Process the sensed data to generate 3D characterization.
- **Give characterization results to Damage Assessment Team for dispositioning.**

[[[O**rbital replacement unit] Tool Change-out Mechanism] **T**ele**v**ision **C**amera]

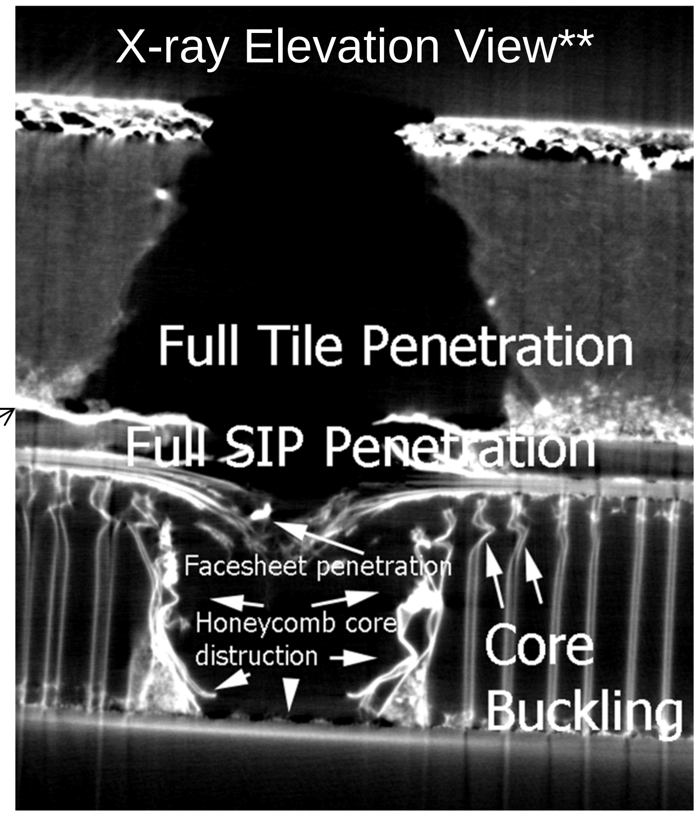
TPS Damage Failure Criteria

- 1) Allowable depth of tile penetration (location dependent specific values)
- 2) Allowable area of Strain Isolation Pad (SIP) penetration (a specific value that was relevant during the study). The SIP is immediately under the tile.
- 3) Allowable degree of core buckling (currently zero core buckling allowed).

LCS* 3D Point Clouds: Elevation Views



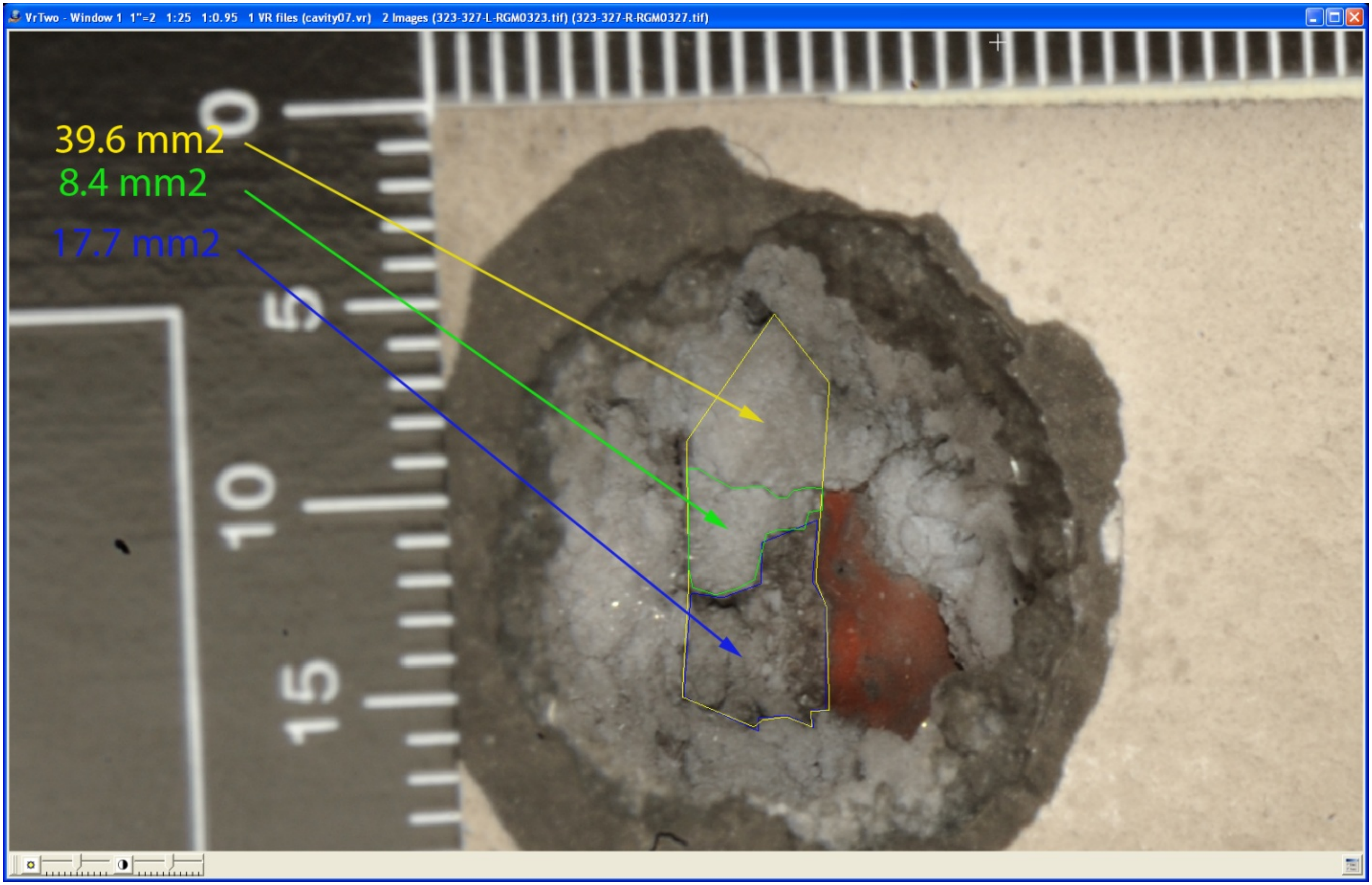
Top of SIP layer



(Fails criterion 3 as well)

*The LCS flew on the Space Shuttle, but is not present on the ISS.
**Ground/lab capability (not on the ISS)

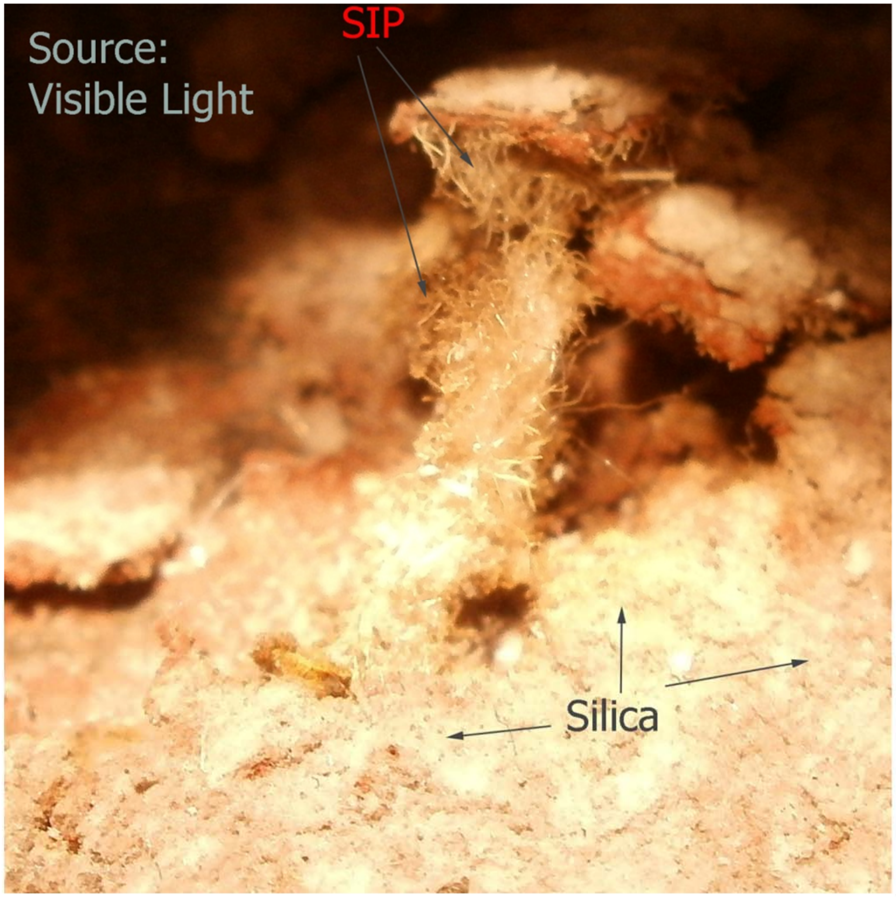
Damage Example: Image of Tile Damage Showing Various Material Layers Down to the Top of the SIP (Red)

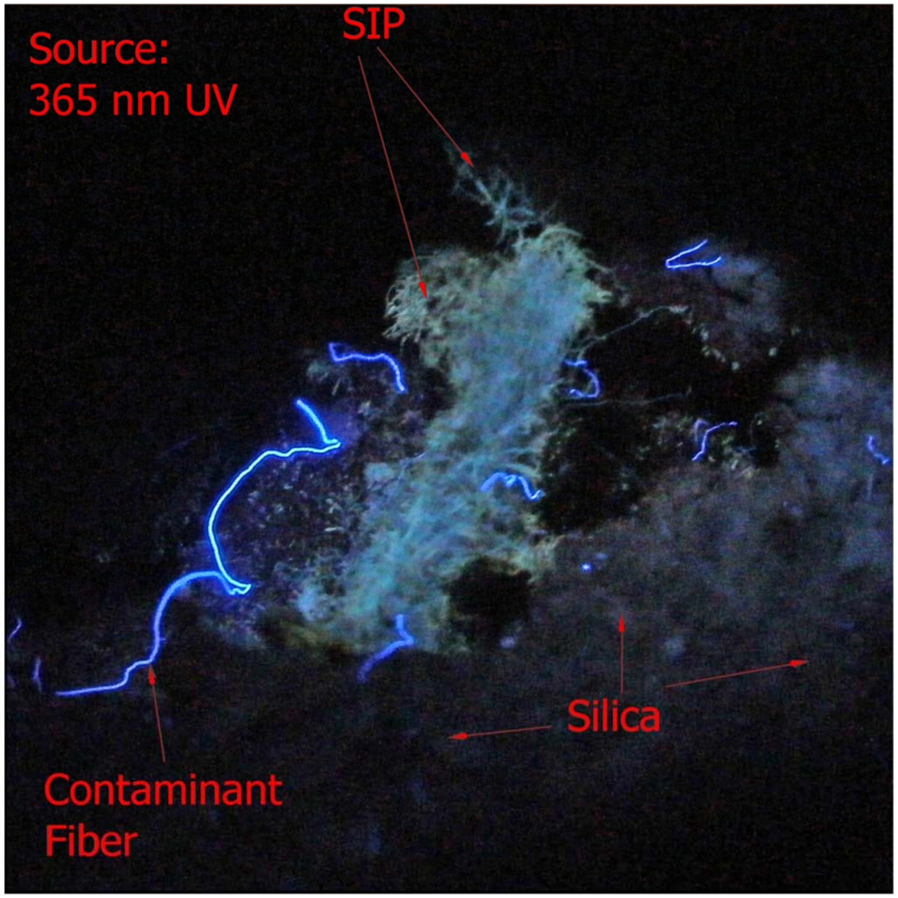


Impact 7 single image, with image-analyst annotations obtained via stereo photogrammetry analysis of an image pair. The bottom segment, indicated with the blue arrow, has an area of 17.7 sq mm or 0.0274 sq. in.

Additional ISAG Inquiry: Discernment of SIP from Tile Silica under 365 nm UV Illumination*

(No existing or currently planned ISS capability)





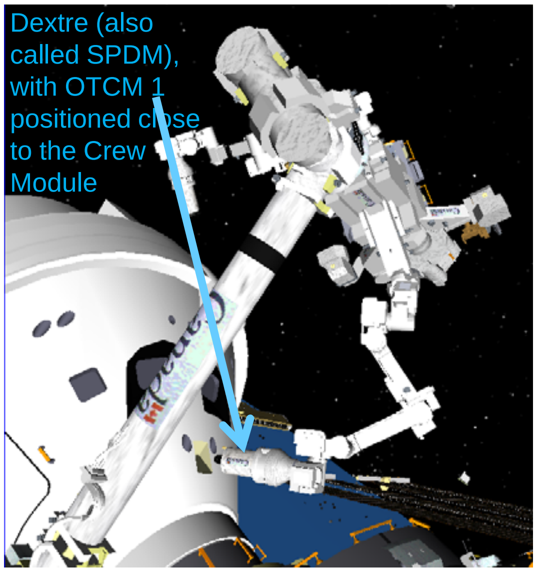
The same view of SIP and silica under visible illumination (left) and UV illumination centered at 365 nm (right). The UV illuminator did include some visible-band illumination, but the fluorescence of the SIP due to UV is distinct.

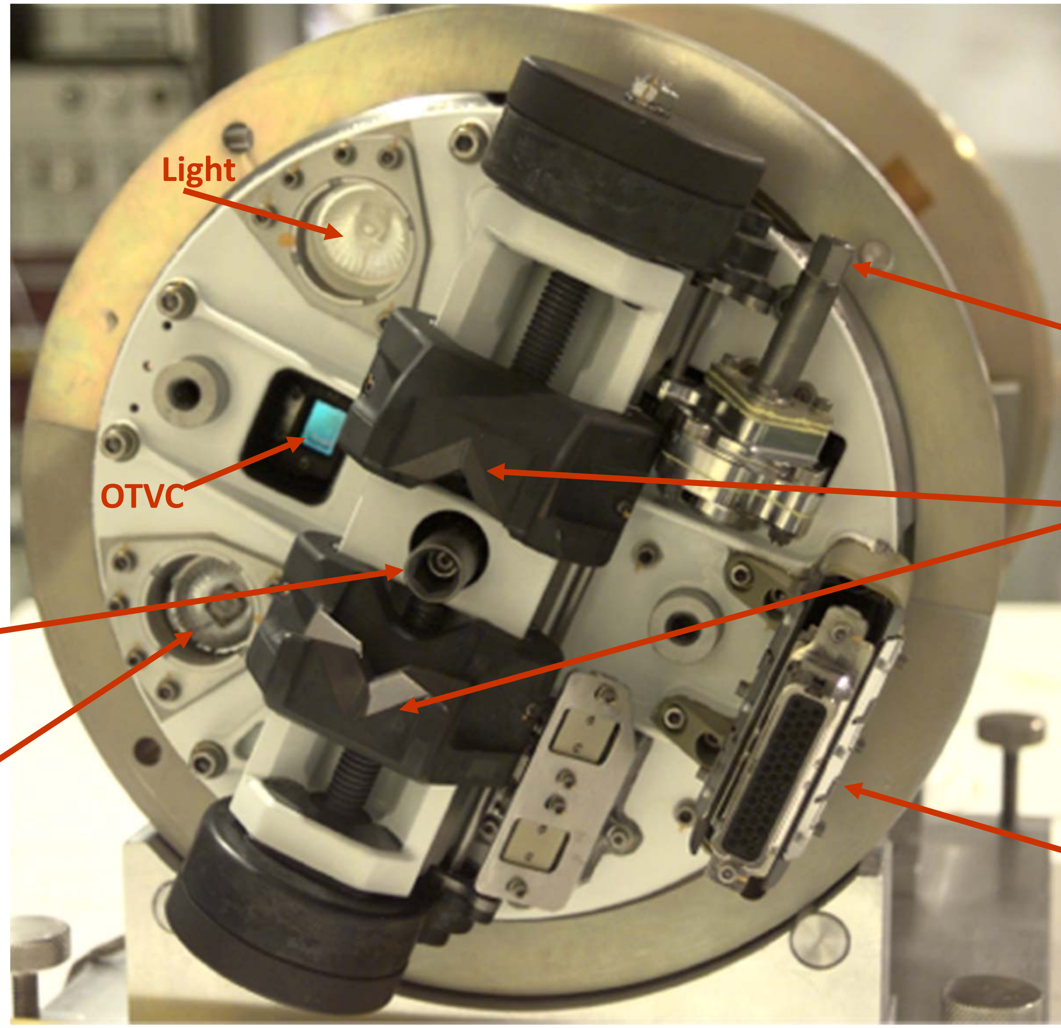
*Ground/lab capability, not ISS.

OTCM Roll Stereo

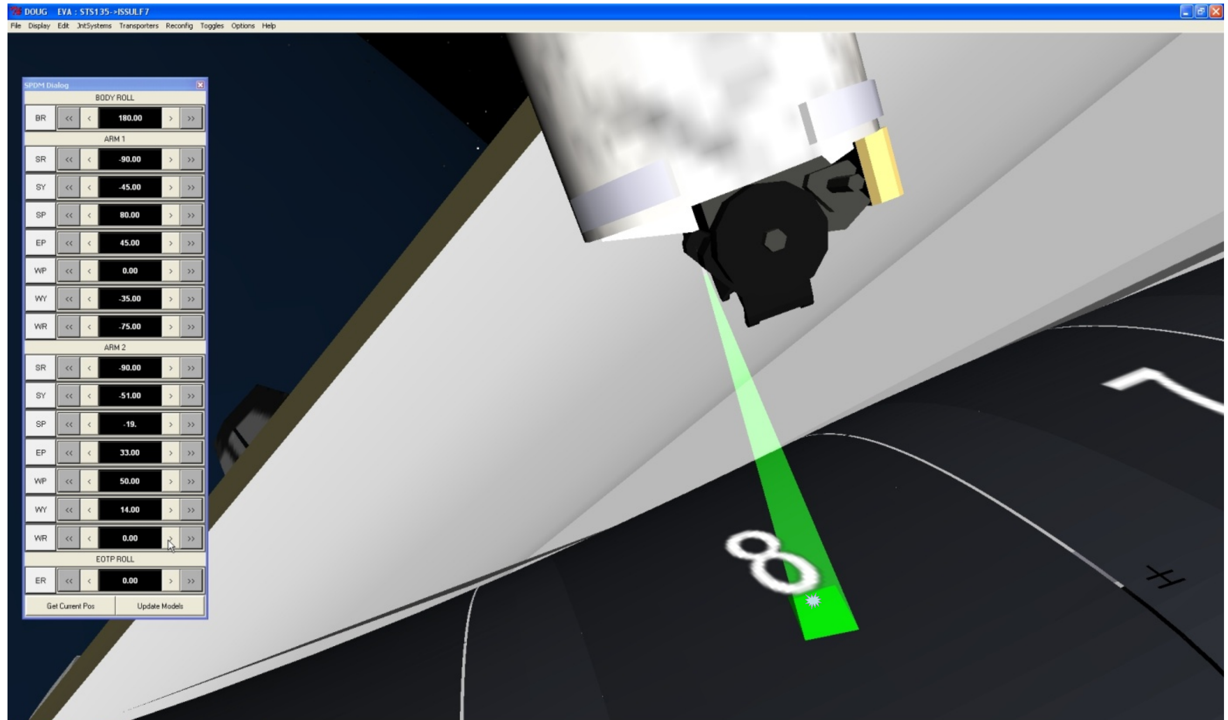
Using One OTVC As a Virtual Stereo Pair for ISS-based Focused Inspection.

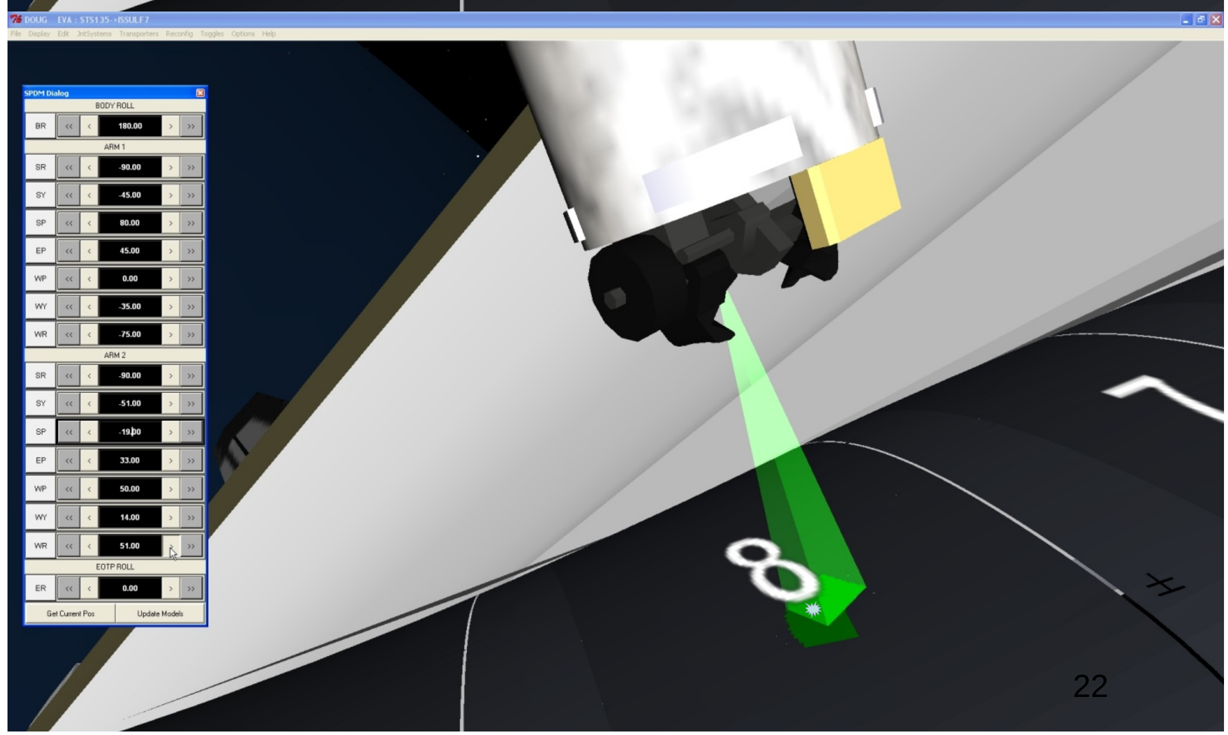
Exploits high precision roll angle information.


Dextre (also
called SPDM),
with OTCM 1
positioned close
to the Crew
Module


Light
EVA
Drive
Bolt
OTVC
Gripper
Socket Drive
Light
Umbilical

OTVC Imaging at 2 OTCM Rotational Positions





Using One OTVC As a Virtual Stereo Pair

- **On Dextre (SPDM), the OTVC is offset from the center axis of the OTCM.**
- **Rotating the OTCM both rotates AND translates the associated OTVC.**
- **Assume rotational information for OTCM is high-precision.**
- **Assume that rotating the OTCM has very little effect on position of the OTCM.**
- **Image surface anomaly from OTVC position 1**
- **Rotate OTCM**
  - If necessary, allow any subsequent shaking of Dextre to dampen out
- **Image surface anomaly from OTVC position 2.**
- **Orient the two OTVC images using stereo tools and Dextre joint-angle information.**
- **Produce stereo model of surface anomaly.**

Depth Precision
vs
Image Resolution

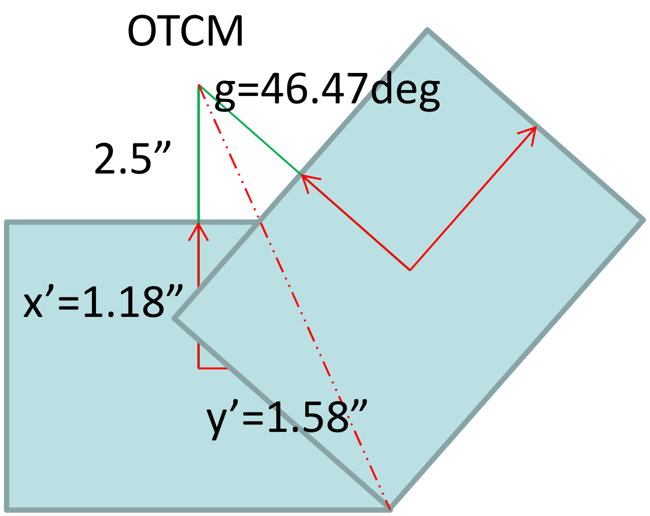
$S_h = (h/B)S_x$

S_h = precision of range (depth)
S_x = precision of horizontal position

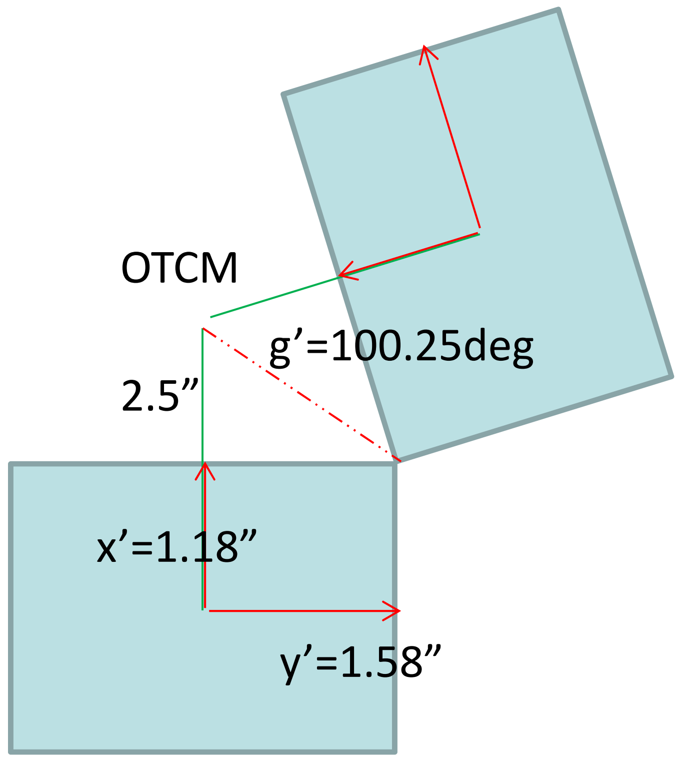
30 degree rotation -> B = 1.29 inches

h	S_h / S_x
13”	10.1
16”	12.4
26”	20.2

Rotational Geometry
16" Range



$\tan(g/2)=y'/(2.5''+x')$



$\tan(g'/2)=y'/(2.5''-x')$

g' is the maximum rotation angle with any image overlap

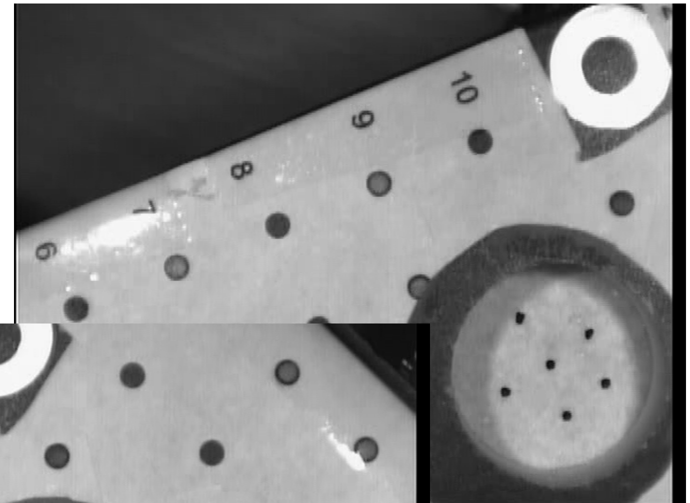
OTCM-Roll Photogrammetry

- **Basic Sequence:**
  - OTCM positioned about 16” away from (and “pointing” at) TPS damage cavity.
  - OTVC captures an image
  - OTCM rolls, moving the OTVC to a different position, separated from the first by baseline B (center to center)
  - OTVC captures another image.
  - Image pair is processed with stereo software for the production of a damage depth estimate, and even a 3D characterization of the cavity (probably requires multiple pairs, collected from different OTCM look angles)
- **Pixel geometry, lens blur, and stereo baseline should support depth measurement resolution on the order of 0.1”. But poor illumination and sometimes-bland surface texture can challenge performance.**
- **Expected resolution degradation due to arm motion should be one to two orders of magnitude lower than geometry-related resolution limitations.**
- **Illumination and bland texture challenges must be dealt with for depth measurement resolution to improve from the 0.2” value estimated in 2011 laboratory analysis (using a related stereo approach).**
  - Lower depth measurement uncertainty is desirable to lessen the probability of unnecessary abandonment of the spacecraft (i.e. “Loss-of-mission”)

OTVC Imagery: Tile with Right-cylindrical Milled Cavities

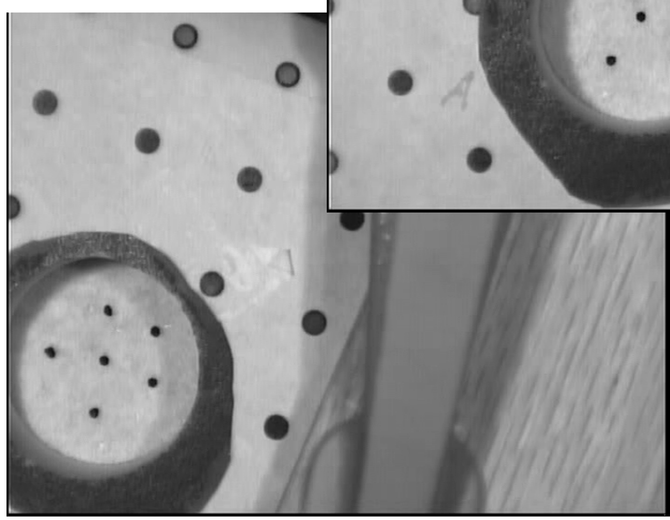
- **Deep Cavity A (Depth TBD)**
- **Cavity is 2.5” offset from roll axis**

+24° Roll
1/125th second
Exposure



0° Roll
1/125th second
Exposure

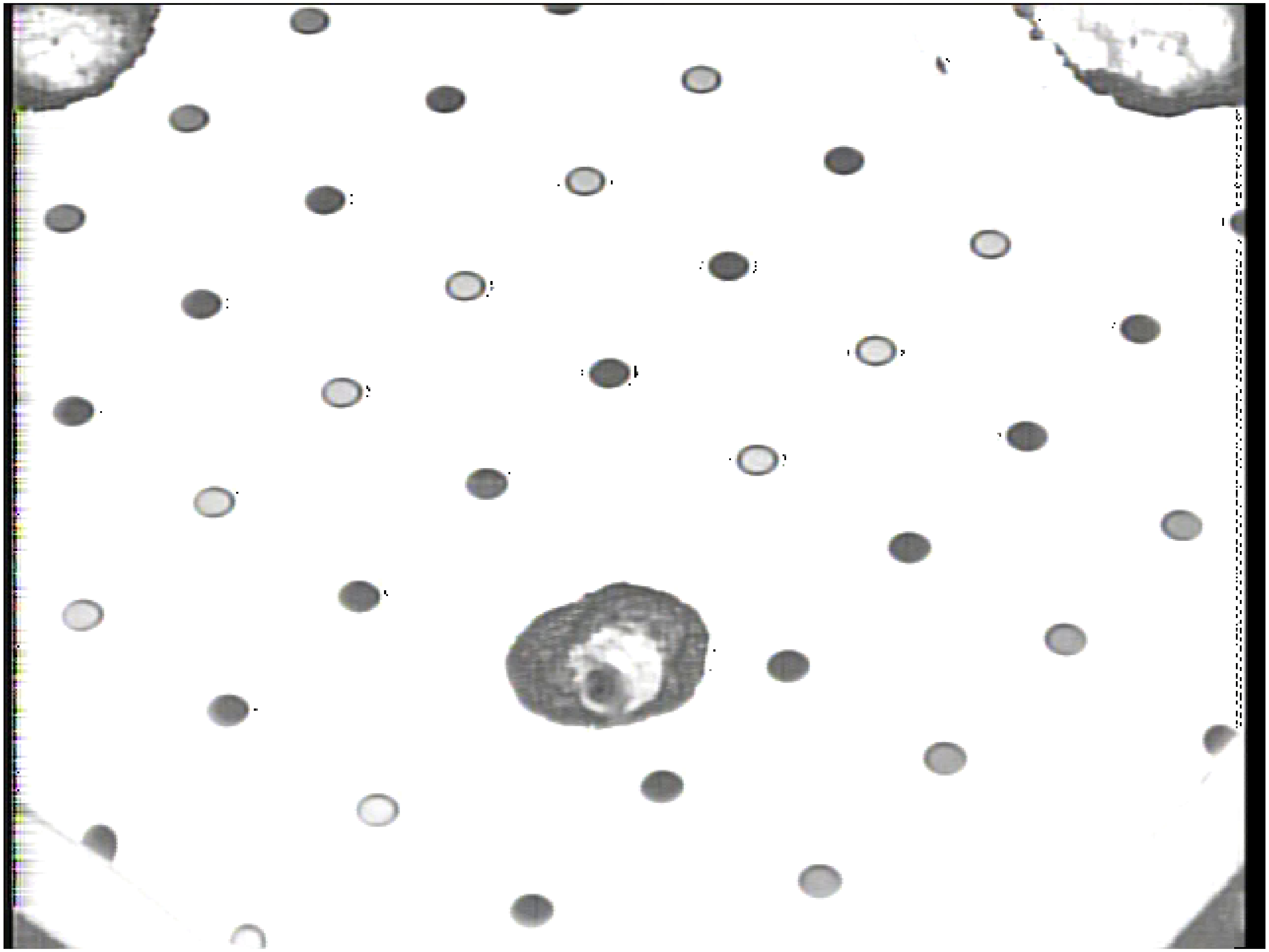
Note: For this imagery, a stand-alone OTVC camera (i.e. no robotics) was used, but the rolling was applied to the test article instead. The camera eyepoint was positioned 2.5” inches from the test article roll axis.



-24° Roll
1/125th second
Exposure

OTVC Image of Hypervelocity Impact

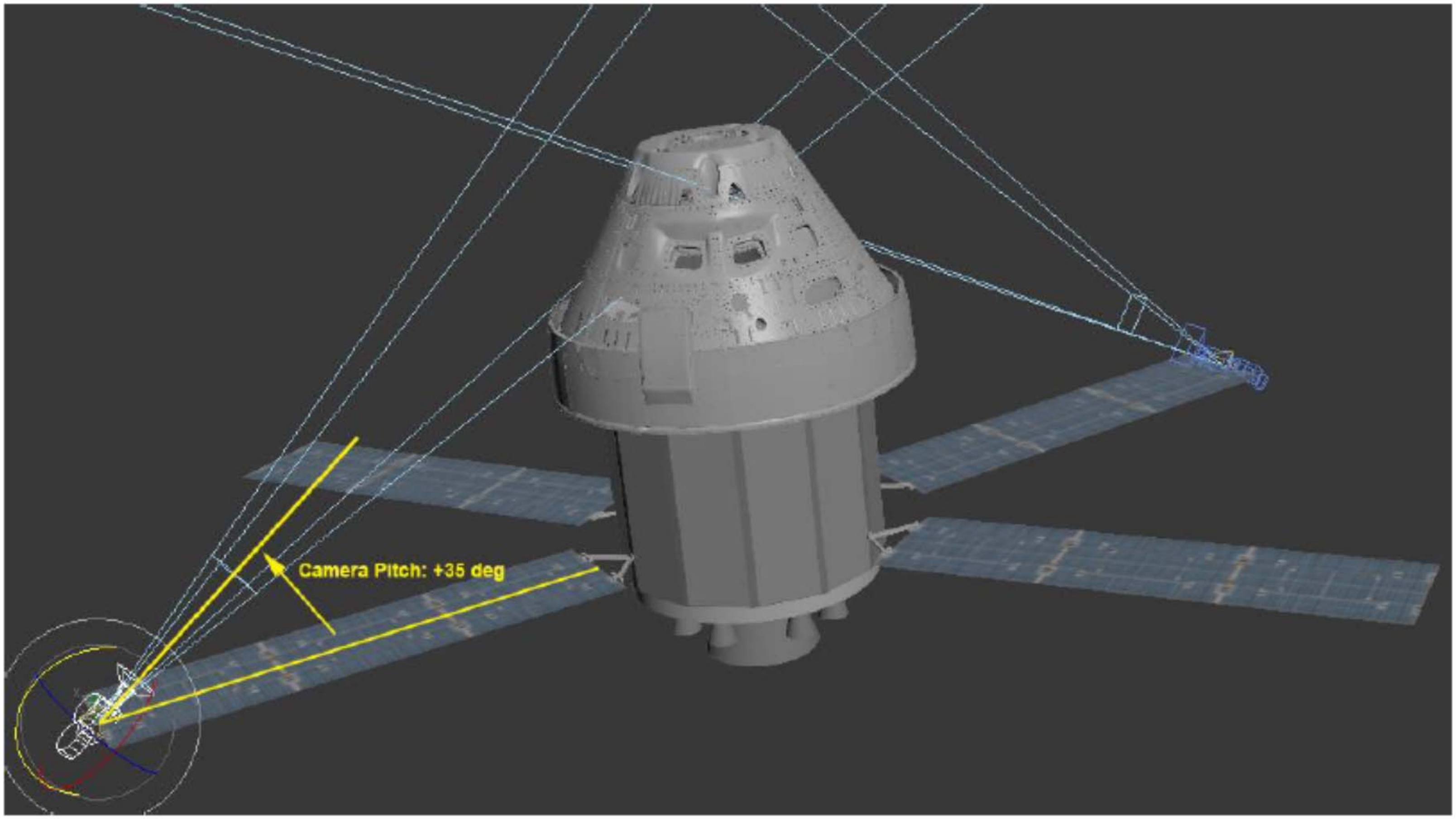
- Tile damage feature that has an entry hole in the size range of interest, with a view to a deep “finger”.
- Difficult, but not impossible to illuminate lower portions of cavity (emphasized here)
- A piece of paper with spots at known centers has been overlaid on the tile to support photogrammetric truth measurements.
- Different exposures can be used to bracket shadows and highlights.



Recent and Planned Upgrades to Inspection Capability Relevant to ISS Visiting Vehicles

- **ODAR upgrades to signal quality**
  - Essentially doubles the vertical resolution in motion video
- **HD upgrades to fixed external cameras**
- **VIPIR – Features additional imagers that could be considered for inspection, but is not currently planned for permanent ISS stowage.**

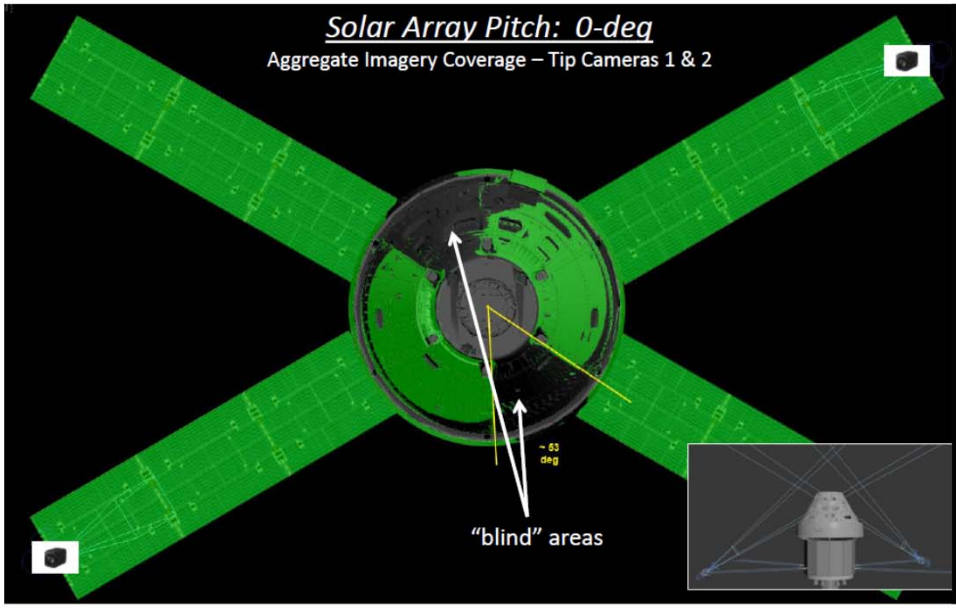
TPS Inspection from SA Cameras

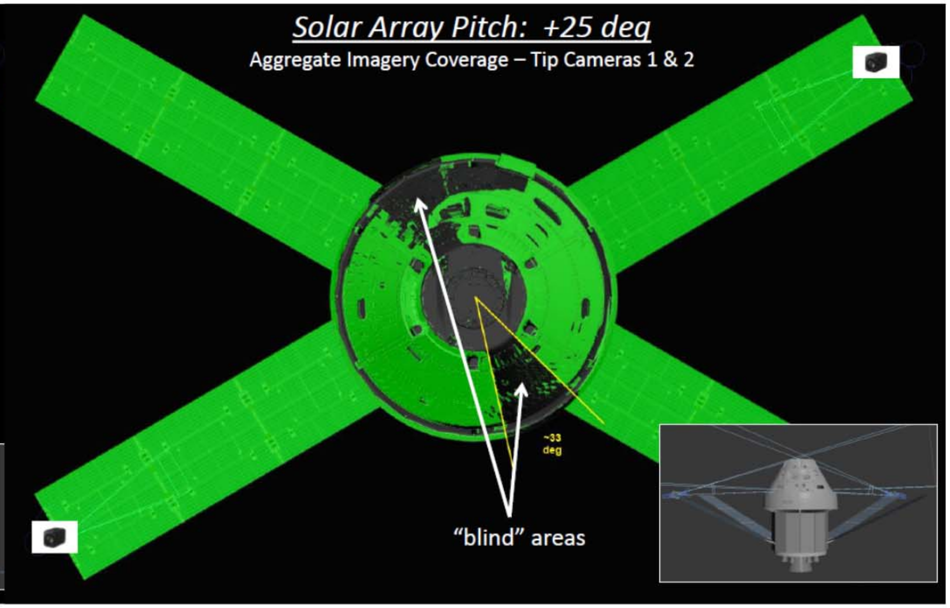


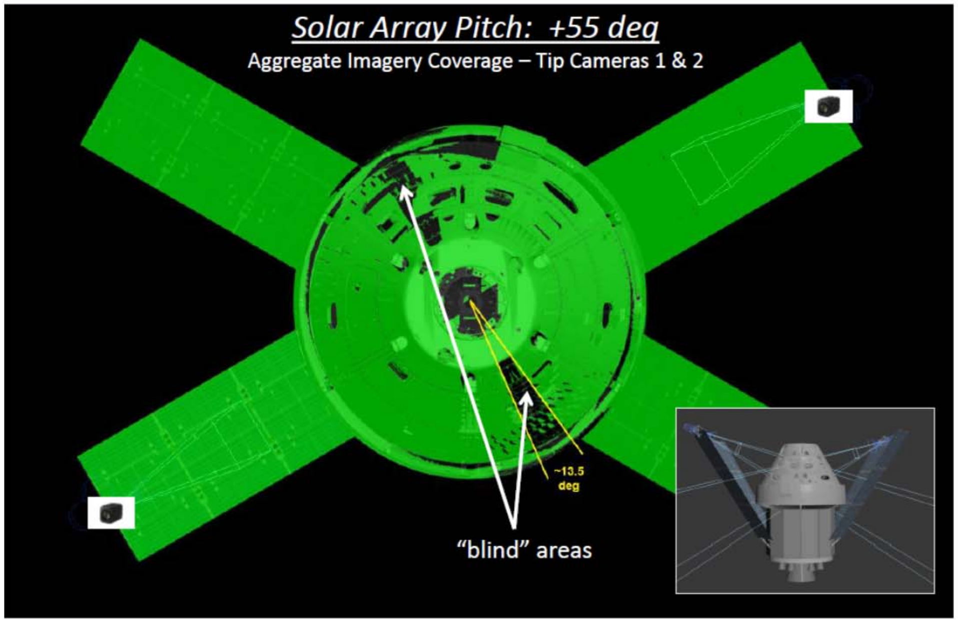
Orion Multi-purpose Crew Vehicle (MPCV), with Crew Module (CM – Top) and European Service Module (SM – lower, with solar arrays). Cameras and sample viewing volumes for a camera-to-array pitch under strong consideration

Camera Line-of-sight Evaluation

(Green Does Not Necessarily Mean Resolution Requirements are Met)







Camera line-of-sight evaluation for 3 different array pitches

Assumes camera-to-array pitch of 35°

Note: These results only apply to a very wide field-of-view lens setting. Zooming in for good detection resolution will constrain coverage and will require different array pitches and rolls.

Post EM2 – Deep Space Inspection Idea

- **A unique, robotic Asteroid Retrieval Vehicle (ARV) is sent to a small TBD boulder and transfers it to a stable "distant retrograde orbit" (DRO) around the Moon.**
- **An Orion spacecraft, with two crewmembers, is sent to rendezvous and dock with the ARV.**
- **After docking, several EVAs take place**
  - Crew members exit the CM through the side hatch door and use a telescoping pole to transfer from the CM to the ARV. The pole will be designed to provide a means for the crew members to avoid contacting the CM TPS as they egress.
  - Crew members transfer along the ARV to the asteroid capture mechanism and then study and determine which samples to bring back within Orion
  - Solar array cameras (if implemented) would be used to capture the operation.
- **A TPS inspection takes place to determine whether or not the CM sustained any damage as part of the operation**
  - Unclear whether this would involve the solar array cameras, EVA photography, or both.
- **Other Orion missions with Orion-based EVAs would benefit from TPS inspection**

*Basic concept described by Gavin Mendeck (Orion) on 27 May, 2014